

[0212] **FIG. 30a.** Wall and fluid temperature profile in micro-channel vaporizer

[0213] **FIG. 30b.** Wall and fluid temperature profile in macro-channel vaporizer

[0214] **FIG. 31a** Vapor quality profile in micro-channel vaporizer

[0215] **FIG. 31b** Vapor quality profile in macro-channel vaporizer

[0216] **FIG. 32** Small bubbles are generated in micro-channels

[0217] **FIG. 33** Large bubbles are generated in large cooling channels

[0218] **FIG. 34a.** Configuration and flow arrangement of a multi-channel reactor

[0219] **FIG. 34b.** An example of the external orifice plate in the header

[0220] **FIG. 35:** Pressure drop and orifice diameter at given heat flux profile for exit quality  $X=0.3$

[0221] **FIG. 36:** Cross flow reactor

[0222] **FIG. 37a.** Definitions and channel dimensions of the model, not drawn to scale.

[0223] **FIG. 38.** Section channel mass flux rates (lower x-axis) and exit temperatures (upper x-axis) for a case (3.0 LPM).

[0224] **FIG. 39:** Variation of Lockhart-Martenelli C factor with quality

[0225] **FIG. 40.** The ratio of the measured heat transfer coefficient to the single phase inlet heat transfer coefficient plotted versus channel exit quality.

#### EXAMPLE 1

##### Modifications of Boiling Fluid Properties

[0226] For many applications, heat removal with the use of a boiling fluid is a closed-loop process. Whereby the boiling fluid is cycled between the boiling unit where heat is captured to a condensation unit where heat is released to a second working fluid or the environment. For these systems, it may be desirable to add surfactant to the boiling working fluid. The surfactant may act to stabilize the small bubbles that are formed during the increased range of nucleate boiling in a microchannel unit operation. The stabilization of small bubbles formed may allow the partial boiling unit to operate with a higher degree of liquid boiling in pass. In other words, a process may be operated with boiling 10%, or 30%, or even 50% or more liquid may be evaporated in a single pass while preventing dryout or hot spot formation. The resulting reduction in total flowrate for the boiling fluid reduces the size of associated ancillary equipment, including pumps and valves.

#### EXAMPLE 2

##### Distributed Partial Boiling in Micro-Channels

[0227] Partial boiling heat transfer in microchannels is integrated with microchannel reactors to conduct exothermic reactions. The cooling channels can be arranged in

various connection patterns to efficiently remove the reaction heat. From the partial boiling curve, the heat flux has a large positive gradient after the single phase cooling section. From the process side where exothermic chemical reactions take place, the heat flux peak, typically occurs shortly after the beginning of the reaction zone. Its exact location is determined by reactant flow rate, the reactor dimension and the characteristics of the catalyst packed bed if the catalyst is used in the reactor. The typical heat flux curve from the process side shows that it peaks near the beginning the reactor. By designing the cooling channels with various types of connections, the heat flux curves from both process side and the cooling side can be aligned so that the partial boiling cooling can meet the desired the heat removal capability locally.

[0228] **FIG. 5** illustrates the main issue when designing the partial boiling heat transfer for exothermic micro-channel reactors. The heat flux from process side-requirement for iso-thermal operation-peaks after a short distance from the beginning of the reaction zone. The typical CHF curve has a negative slope along the cooling channel. With the dash-line CHF curve, given the conditions of pressure in the cooling channel, coolant flow rate, coolant inlet temperature and channel gap size, the dry-out will occur near the peak heat flux requirement. In order to make the partial boiling run stably, the parameters can be adjusted to give the CHF curve above the heat flux curve everywhere along the length.

[0229] Configuration 1: A cooling channel can be divided to improve performance for partial boiling. The coolant channel can have an initial area with single phase cooling followed by a second, subdivided region could have one, two or more walls dividing the coolant channels into sub-channels in which partial boiling occurs; for example, subdivided into two channels each of which share a thermal transfer wall with a reaction channel. The division walls can be parallel or, more preferably, perpendicular to the height of the reaction channels so that heat is conducted through the wall directly from the reaction channel to the coolant channel.

[0230] Configuration 2: Single cooling channel is divided into several sub-cooling channels. See **FIG. 7**. The division location is designed to align with the peak of the heat flux profile from the process side. The smaller gap size of the partial cooling channels can achieve higher critical heat flux (CHF). Other design parameters are the dimensions of the sub-cooling channel, width (W) and gap height (H). The aspect ratio of W/H is in the range 5 to 10. By splitting the single cooling channel to several smaller cooling channels, all sides of the cooling channels are heat transfer surfaces. Compared to the cooling channels with the same size of the reaction channels, the heat transfer surface area per unit of the reactor volume is increased to 2 to 3 times.

[0231] Configuration 3: The cooling channel is designed such that the gap size varies along the cooling channel. The cooling fluid stream speeds up where the gap size is small. The higher critical heat flux is able to achieve locally where the gap size is small. The exact gap size profile is designed upon the heat removal need from the process side. See **FIG. 8**.